Chapter 3. Stoichiometry: Calculations with Chemical Formulas and Equations

3.1 Chemical Equations

- Lavoisier observed that mass is conserved in a chemical reaction.
  - This observation is known as the **law of conservation of mass.**
- The quantitative nature of chemical formulas and reactions is called **stoichiometry**.
- **Chemical equations** give a description of a chemical reaction.
- There are two parts to any equation:
  - **Reactants** (written to the left of the arrow) and
  - **Products** (written to the right of the arrow):

$$2H_2 + O_2 \rightarrow 2H_2O$$

- There are two sets of numbers in a chemical equation:
  - Numbers in front of the chemical formulas (called stoichiometric *coefficients*) and
  - Numbers in the formulas (they appear as subscripts).
- Stoichiometric coefficients give the *ratio* in which the reactants and products exist.
- The subscripts give the ratio in which the atoms are found in the molecule.
  - Example:
    - H_2O means there are <u>two H atoms</u> for each one molecule of water.
    - $2H_2O$ means that there are <u>two water molecules</u> present.
- Note: In $2H_2O$ there are *four* hydrogen atoms present (two for each water molecule).
- Matter cannot be lost in chemical reactions.
  - Therefore, the products of a chemical reaction have to account for all the atoms present in the reactants.
- Consider the reaction of methane with oxygen:

$$CH_4 + O_2 \rightarrow CO_2 + H_2O$$

- Counting *atoms* in the reactants:
  - 1 C;
  - 4 H; and
  - 2 O.
- In the products:
  - 1 C;
  - 2 H; and
  - 3 O.
- It appears as though H has been lost and C has been created.
- To balance the equation, we adjust the stoichiometric coefficients:

$$CH_4 + \mathbf{2}O_2 \rightarrow CO_2 + \mathbf{2}H_2O$$

3.2 Patterns of Chemical Reactivity

Using the Periodic Table

- As a consequence of the good ordering of the periodic table, the properties of compounds of elements vary in a systematic manner.
- Example: All the alkali metals (M) react with water as follows:

$$2M(s) + 2H_2O(l) \rightarrow 2MOH(aq) + H_2(g)$$

  - The reactions become more vigorous as we move from Li to Cs.
  - Sodium reacts with water to produce an orange flame.
  - Potassium reacts with water to produce a blue flame.
  - The reaction of potassium with water produces so much heat that the hydrogen gas produced usually ignites with a loud pop.

Combustion in Air

- **Combustion reactions** are rapid reactions that produce a flame.
  - Combustion is the burning of a substance in air.
  - Example: Propane combusts to produce carbon dioxide and water:

$$C_3H_8(g) + 5O_2(g) \rightarrow 3CO_2(g) + 4H_2O(l)$$

Combination and Decomposition Reactions

- In **combination reactions** two or more substances react to form one product.
- Combination reactions have more reactants than products.
  - Consider the reaction:

$$2Mg(s) + O_2(g) \rightarrow 2MgO(s)$$

    - Since there are fewer products than reactants, the Mg has combined with O_2 to form MgO.
    - Note that the structure of the reactants has changed:
      - Mg consists of closely packed atoms, and O_2 consists of dispersed molecules.
      - MgO consists of a lattice of Mg^{2+} and O^{2-} ions.
- In **decomposition reactions** one substance undergoes a reaction to produce two or more other substances.
- Decomposition reactions have more products than reactants.
  - Consider the reaction that occurs in an automobile air bag:

$$2NaN_3(s) \rightarrow 2Na(s) + 3N_2(g)$$

    - Since there are more products than reactants, the sodium azide has decomposed into Na metal and N_2 gas.

3.3 Atomic and Molecular Weights

The Atomic Mass Scale

- Consider 100 g of water:
  - Upon decomposition 11.1 g of hydrogen and 88.9 g of oxygen are produced.
  - The mass ratio of O to H in water is 88.9/11.1 ≅ 8.
  - Therefore, the mass of O is 2 x 8 = 16 times the mass of H.
  - If H has a mass of 1, then O has a *relative mass* of 16.
  - We can measure atomic masses accurately using a mass spectrometer.
  - We know that ^1H has a mass of 1.6735×10^{-24} g, and ^{16}O has a mass of 2.6560×10^{-23} g.
- Atomic mass units (amu) are convenient units to use when dealing with extremely small masses of individual atoms.
- 1 amu = 1.66054×10^{-24} g and 1 g = 6.02214×10^{23} amu
- By definition, the mass of ^{12}C is exactly 12 amu.

Average Atomic Masses

- We average the masses of isotopes using their masses and relative abundances to give the average atomic mass of an element.
  - Naturally occurring C consists of 98.892% ^{12}C (12 amu) and 1.108% ^{13}C (13.00335 amu).
  - The average mass of C is
    (0.98892)(12 amu) + (0.01108)(13.00335) = 12.011 amu
- **Atomic weight** (AW) is also known as average atomic mass.
- Atomic weights are listed on the periodic table.

Formula and Molecular Weights

- **Formula weight** (FW) is the sum of atomic weights for the atoms shown in the chemical formula.
  - Example: FW (H_2SO_4)
    = 2AW(H) + AW(S) + 4AW(O)
    = 2(1.0 amu) + 32.1 amu + 4(16.0 amu)
    = 98.1 amu
- **Molecular weight** (MW) is the sum of the atomic weights of the atoms in a molecule as shown in the molecular formula.
  - Example: MW ($C_6H_{12}O_6$)
    = 6(12.0 amu) + 12 (1.0 amu) + 6 (16.0 amu)
    = 180.0 amu
- Formula weight of the repeating unit is used for ionic substances.
  - Example: FW (NaCl)
    = 23.0 amu + 35.5 amu
    = 58.5 amu

Percentage Composition from Formulas

- Percent composition is obtained by dividing the mass contributed by each element (number of atoms times AW) by the formula weight of the compound and multiplying by 100.

The Mass Spectrometer

- Mass spectrometers are pieces of equipment designed to measure atomic and molecular masses accurately.
- The sample is converted to positive ions by collisions with a stream of high energy electrons upon entering the spectrometer.
- The charged sample is accelerated using an applied voltage.
- The ions are then passed into an evacuated tube and through a magnetic field.
- The magnetic field causes the ions to be deflected by different amounts depending on their mass.
- The ions are then detected.

3.4 The Mole

- The mole is a convenient measure of chemical quantities (just as a dozen is a convenient way to measure cooking quantities).
- 1 mole of something = 6.0221421×10^{23} of that thing.
  - This number is called **Avogadro's number.**
  - Thus 1 mole of carbon atoms = 6.0221421×10^{23} carbon atoms.

Molar Mass

- The mass in grams of 1 mole of a substance is said to be the **molar mass** of that substance. Molar mass is expressed in units of g/mol (also written $g{\cdot}mol^{-1}$).
- The mass of 1 mole of ^{12}C = 12 g.
- The molar mass of a molecule is the sum of the molar masses of the atoms.
  - Example: The molar mass of N_2 = 2 x (molar mass of N).
- Molar masses for elements are found on the periodic table.
- Formula weights are numerically equal to the molar mass.

Interconverting Masses, Moles, and Number of Particles

- Look at units:
  - Mass: g
  - Moles: mol
  - Molar mass: g/mol
  - Number of particles: $6.022 \times 10^{23}\ mol^{-1}$ (Avogadro's number).
  - Note: g/mol x mol = g (i.e. molar mass x moles = mass), and
  - mol x mol^{-1} = a number (i.e. moles x Avogadro's number = molecules).
- To convert between grams and moles, we use the molar mass.
- To convert between moles and molecules we use Avogadro's number.

3.5 Empirical Formulas from Analyses

- Recall that the empirical formula gives the *relative* number of atoms in the molecule.
- Finding empirical formula from mass percent data:
  - We start with the mass percent of elements (i.e., empirical data) and calculate a formula.
    - Assume we start with 100 g of sample.
    - The mass percent then translates as the number of grams of each element in 100 g of sample.
    - From these masses, we can calculate the number of moles (using the atomic weight from the periodic table).
    - The lowest whole-number ratio of moles is the empirical formula.
- Finding the empirical mass percent of elements from the empirical formula:
  - If we have the empirical formula, we know how many moles of each element are present in 1 mole of the sample.
  - Next, we use molar masses (or atomic weights) to convert to grams of each element.
  - We divide the grams of each element by grams of 1 mole of sample to get the fraction of each element in 1 mole of sample.
  - We multiply each fraction by 100 to convert to a percent.

Molecular Formula from Empirical Formula

- The empirical formula (relative ratio of elements in the molecule) may not be the molecular formula (actual ratio of elements in the molecule).
  - Example: Ascorbic acid (vitamin C) has the empirical formula $C_3H_4O_3$.
  - The molecular formula is $C_6H_8O_6$.
  - To get the molecular formula from the empirical formula, we need to know the molecular weight, MW.
  - The ratio of molecular weight (MW) to formula weight (FW) of the empirical formula must be a whole number.

Combustion Analysis

- Empirical formulas are routinely determined by combustion analysis.
- A sample containing C, H, and O is combusted in excess oxygen to produce CO_2 and H_2O.
- The amount of CO_2 gives the amount of C originally present in the sample.
- The amount of H_2O gives the amount of H originally present in the sample.
  - Watch stoichiometry: 1 mol H_2O contains 2 mol H.
- The amount of O originally present in the sample is given by the difference in the amount of sample and the amount of C and H accounted for.
- More complicated methods can be used to quantify the amounts of other elements present, but they rely on analogous methods.

3.6 Quantitative Information from Balanced Equations

- The coefficients in a balanced chemical equation give the relative numbers of molecules (or formula units) involved in the reaction.
- We can interpret this equation as the *number of moles of reactant* that are required to give the *number of moles of product.*
  - A *stoichiometric ratio* is the ratio of the number of moles of one reactant or product to the number of moles of another reactant or product.
- It is important to realize that the stoichiometric ratios are the ideal proportions in which reactants are needed to form products.
- The real ratio of reactants and products present in the laboratory needs to be measured (in grams and converted to moles).
- The number of grams of a reactant cannot be *directly* related to the number of grams of a product.
  - To get grams of product from grams of reactant:
    - Convert grams of reactant to moles of reactant (use molar mass).
    - Convert moles of reactant to moles of desired product (use the stoichiometric ratio from the balanced chemical equation).
    - Convert moles back into grams for desired product (use molar mass).

3.7 Limiting Reactants

- It is not necessary to have all reactants present in stoichiometric amounts.
- Often, one or more reactants are present in excess.
- Therefore, at the end of the reaction, those reactants present in excess will still be in the reaction mixture.
- The one or more reactants that are completely consumed are called the **limiting reactants.**
- Consider 10 H_2 molecules mixed with 7 O_2 molecules that react to form water.
  - The balanced chemical equation tells us that the stoichiometric ratio of H_2 to O_2 is 2 to 1:

$$2H_2(g) + O_2(g) \rightarrow 2H_2O(l)$$

  - This means that our 10 H_2 molecules require 5 O_2 molecules (2:1).
  - Since we have 7 O_2 molecules, our reaction is *limited* by the amount of H_2 we have (the O_2 is present in excess).
  - So, all 10 H_2 molecules can (and do) react with 5 of the O_2 molecules to produce 10 H_2O molecules.
  - At the end of the reaction, 2 O_2 molecules remain unreacted.

Theoretical Yields

- The amount of product predicted from stoichiometry taking into account limiting reagents is called the **theoretical yield.**
- The **percent yield** relates the actual yield (amount of material recovered in the laboratory) to the theoretical yield.

$$\text{Percent yield} = \frac{\text{actual yield}}{\text{theoretical yield}} \times 100$$

SAMPLE EQUATIONS FROM OLD AP EXAMINATIONS

1. Magnesium metal is burned in nitrogen gas

2. Sulfur dioxide gas is passed over solid calcium oxide

3. Lead foil is immersed in silver nitrate solution.

4. A solution of ammonium sulfate is added to a saturated solution of barium hydroxide

5. Acetic acid solution is added to a solution of sodium hydrogen carbonate

6. Solid sodium dichromate is added to an acidified solution of sodium iodide.

7. A drop of potassium thiocyanate is added to a solution of iron (III) chloride.

8. Ethanol is completely burned in air

9. Hydrogen gas is passed over hot iron (III) oxide

10. Solutions of potassium iodide and potassium iodate are mixed in acid

11. Dilute sulfuric acid is added to solid calcium fluoride

12. Solid ammonium carbonate is heated

13. Methane gas is mixed with an excess of chlorine gas

14. A concentrated solution of ammonia is added to a suspension of zinc hyroxide

15. Hydrogen peroxide is added to an acidified solution of sodium bromide

16. Dilute hydrochloric acid is added to a dilute solution of mercury (I) nitrate

17. Dilute sulfuric acid is added to a solution of barium acetate

18. Solid phosphorous pentachloride is added to excess water

19. A solution of hydrogen peroxide is catalytically decomposed

20. Powdered iron is added to a solution of iron (III) sulfate

21. Ammonium chloride crystals are added to a solution of sodium hydroxide

22. Chlorine gas is bubbled into a solution of sodium bromide

23. A precipitate is formed when solutions of trisodium phosphate and calcium chloride are mixed

24. Benzene is treated with bromine in the presence of a catalyst

25. A solution of copper (II) sulfate is electrolyzed using inert electrodes

26. Hydrogen sulfide gas is bubbled through excess potassium hydroxide solution

27. Solutions of silver nitrate and sodium chromate are mixed

28. Sodium hydroxide solution is added to a precipitate of aluminum hydroxide in water.

29. Solid sodium sulfite is added to water.

30. A solution of formic acid, HCOOH, is oxidized by an acidified solution of potassium dichromate

31. Ammonia gas and carbon dioxide gas are bubbled into water

32. Concentrated hydrochloric acid solution is added to solid manganese(IV) oxide and the reactants are heated

33. Solutions of sodium fluoride and dilute hydrochloric acid are mixed

34. A saturated solution of barium hydroxide is mixed with a solution of iron (III) sulfate

35. A solution of ammonium sulfate is added to a potassium hydroxide solution

Equations of the Week

Write net [redacted] equations for the following:

a. The complete combustion of methane (CH_4)

b. The decomposition of Magnesium chlorate

c. Chorine gas is bubbled into an aqueous solution of sodium iodide

d. Magnesium ribbon is burned in air

REACTIONS

COMBINATION REACTIONS:

GpIA or Ca, Ba, Sr

1) Metal oxide + water → a base

Ex. Solid calcium oxide is added to water

$$CaO_{(s)} + HOH_{(l)} \rightarrow Ca(OH)_{2(aq)}$$

The base is calcium hydroxide

<u>NET IONIC FORM:</u>

$$CaO + HOH \rightarrow Ca^{2+} + 2OH^{-}$$

Ex. Solid sodium oxide is added to water

$$Na_2O_{(s)} + HOH_{(l)} \rightarrow 2NaOH_{(aq)}$$

The base is sodium hydroxide

<u>NET IONIC FORM:</u>

$$Na_2O + HOH \rightarrow 2Na^{+} + 2OH^{-}$$

ANY Gp IA metal oxide (Li_2O, Na_2O, K_2O, Rb_2O, Cs_2O) or the following Gp 2A METAL OXIDES (CaO, BaO, SrO) will react in water to form <u>SOLUBLE BASES</u> OR <u>SOLUBLE METAL HYDROXIDES</u>

2) Nonmetal oxide + water → an acid

Ex. Sulfur DIOXIDE + WATER → SULFUROUS ACID

$SO_2 + HOH \rightarrow H_2SO_{3(aq)}$

NET IONIC FORM:

$SO_2 + HOH \rightarrow H^+ + HSO_3^-$

Ex. Sulfur TRIOXIDE + H_2O → SULFURIC ACID

$SO_3 + HOH \rightarrow H_2SO_{4(aq)}$

NET IONIC FORM:

$SO_3 + HOH \rightarrow H^+ + HSO_4^-$

Ex. Nitrogen dioxide + WATER → nitric acid

$NO_2 + HOH \rightarrow HNO_{3(aq)}$

NET IONIC FORM:

$NO_2 + HOH \rightarrow H^+ + NO_3^-$

Ex. DInitrogen pentoxide + WATER → nitric acid

$N_2O_5 + HOH \rightarrow H^+ + NO_3^-$

Ex. Carbon dioxide + WATER → carbonic acid

$CO_2 + HOH \rightarrow H_2CO_3$

NET IONIC FORM:

$CO_2 + HOH \rightarrow H^+ + HCO_3^-$

3. Metal oxide + nonmetal oxide → salt containin oxygen

Ex. Calcium oxide + sulfurdioxide → calcium sulfate

$CaO + SO_2 \rightarrow CaSO_3$

Ex. A mixture of solid calcium oxide and solid tetraphosphorous decaoxide is heated.

$CaO_{(s)} + P_4O_{10\,(s)} \rightarrow Ca_3(PO_4)_{2\,(s)}$

Decomposition reaction (reverse of combination reactions)

4. Base → metaloxide + water

Ex. calcium hydroxide → calcium oxide and water

$Ca(OH)_2 \rightarrow CaO + HOH$

Ex. Magnesium hydroxide → magnesium oxide and water

$Mg(OH)_2 \rightarrow MgO + HOH$

Ex. Sodium hydroxide → sodium oxide and water

$NaOH \rightarrow Na_2O + HOH$

5. Acid containing oxygen → nonmetal oxide and water

Ex. Carbonic acid → carbon dioxide and water

$H_2CO_3 \rightarrow CO_2 + HOH$

Ex. Sulfuric acid → sulfur trioxide and water

$H_2SO_4 \rightarrow SO_3 + HOH$

Ex. Nitric acid → nitrogen dioxide and water

$HNO_3 \rightarrow NO_2 + H_2O$

6. Salt containing oxygen → metal oxide + nonmetal oxide

Ex. calcium carbonate → calcium oxide + carbon dioxide

$CaCO_3 \rightarrow CaO_{(s)} + CO_2$

Ex. Solid magnesium carbonate is heated in a crucible

$MgCO_3 \rightarrow MgO + CO_2$

7. Decomposition of hydrogen peroxide and hydrazine

Hydrogen peroxide decomposition:

$H_2O_2 \rightarrow H_2O + O_2$

Hydrazine decomposition:

$N_2H_4 \rightarrow N_2 + H_2$

8. <u>Chlorates</u> decompose in the presence of heat to yield metallic chlorides and oxygen gas

Ex. Solid potassium chlorate is heated in a ~~test~~ tube

$KClO_3 \rightarrow KCl + O_2$

9. Electrolysis decomposes compounds into their elements

Ex. a dilute solution of sulfuric acid is electrolyzed between platinum electrodes

$H_2O \rightarrow H_2 + O_2$

In this case the voltage required to decompose water is less than the voltage required ~~to~~ decompose H_2SO_4

10. Metals react with nonmetals to form salts

Ex. Solid magnesium or magnesium ribbon is burned in pure nitrogen gas ~Mg^{2+} ~N^{3-}
~magnesium nitride

$Mg_{(s)} + N_{2(g)} \rightarrow Mg_3N_{2(s)}$

Ex. Solid lithium is burned or heated in pure nitrogen gas
~product is lithium nitride ~$Li^{+}N^{3-}$ Li_3N

$Li_{(s)} + N_{2(g)} \rightarrow Li_3N_{(s)}$

Ex. Solid potassium is heated in the presence of chlorine gas ~product is potassium chloride
$K^{+}Cl^{-} \rightarrow KCl$

$K_{(s)} + Cl_{2(g)} \rightarrow KCl_{(s)}$

11. Gp IA metals react with water to Produce an alkali base and hydrogen gas

Ex. Solid sodium is added to water

$Na_{(s)} + HOH \rightarrow NaOH_{(aq)} + H_{2(g)}$

→ **NET IONIC FORM** is:

$Na_{(s)} + HOH \rightarrow Na^+ + OH^- + H_2$

12. Metal hydrides react with water to produce a metallic base and hydrogen gas

Ex. Solid sodium hydride is added to water

$NaH_{(s)} + HOH \rightarrow NaOH_{(aq)} + H_{2(g)}$

→ **NET IONIC FORM** is:

$NaH + HOH \rightarrow Na^+ + OH^- + H_2$

13. Formation of an Insoluble precipitate

↳ REQUIRES KNOWLEDGE OF SOLUBILITY OF COMPOUNDS.

↳ DO NOT HAVE TO BE BALANCED IN THIS SECTION.

Example :

Solid potassium dichromate is added to an aqueous solution of lead II nitrate

$$(K^+ + Cr_2O_7^{2-}) + (Pb^{2+} + NO_3^-) \rightarrow PbCr_2O_{7(s)} + (K^+ + NO_3^-)$$

NET IONIC!

$$Pb^{2+} + Cr_2O_7^{2-} \rightarrow PbCr_2O_7$$

Example :

Solutions of sodium iodide and lead nitrate are mixed

$$(Na^+ + I^-) + (Pb^{2+} + NO_3^-) \rightarrow PbI_2 + (Na^+ + NO_3^-)$$

NET IONIC: $Pb^{2+} + I^- \rightarrow PbI_2$

Example: solutions of silver nitrate and sodium chromateare mixed

$(Ag^+ + NO_3^-) + (Na^+ + CrO_4^{2-}) \rightarrow Ag_2CrO_{4(s)} + (Na^+ + NO$

NET IONIC $Ag^+ + CrO_4^{2-} \rightarrow Ag_2CrO_4$

14. Halide testing equations

* The ability of chlorine to replace I^- and Br^- ions in solution is used in testing for iodides and bromides.

F_2 can replace Cl^-, Br^-, and I^-

Cl_2 can replace Br^- and I^-

Br_2 can replace I^-

Include TTE + [illegible]

Example. Chlorine gas is bubbled through a solution of potassium bromide

$Cl_2 + (K^+ + Br^-) \rightarrow Br_2 + (K^+ + Cl^-)$

K^+ is a specator ion

NET IONIC: $Cl_2 + Br^- \rightarrow Br_2 + Cl^-$

Example Bromine water is added to a solution of sodium iodide

H_2O with Br_2 dissolved in it.

$Br_2 + (Na^+ + I^-) \rightarrow I_2 + (Na^+ + Br^-)$

NET IONIC $Br_2 + I^- \rightarrow I_2 + Br^-$

USEFUL CLASSIFICATIONS OF COMPOUNDS

1. ACIDS - COMPOUNDS WITH FORMULAS THAT BEGIN WITH H
   HCl, HNO_3
   THE NUMBER OF FREQUENTLY ENCOUNTERED STRONG ACIDS (ACIDS THAT ARE PRESENT IN SOLUTION VERY LARGELY AS IONS RATHER THAN AS MOLECULES) IS SMALL AND YOU SHOULD KNOW THEM BY NAME AND FORMULA
   HCl - hydrochloric acid
   HBr - hydrobromic acid
   HI - hydroiodic acid
   HNO_3 - nitric acid
   H_2SO_4 - sulfuric acid
   $HClO_4$ - perchloric acid

AS A FIRST APPROXIMATION, ALL OTHER ACIDS MAY BE CONSIDERED WEAK(PRESENT IN SOLUTION LARGELY AS MOLECULES) UNLESS AND UNTIL THE STUDENT LEARNS OTHERWISE.

2. BASES - COMPOUNDS WITH FORMULAS THAT END WITH OH
   $NaOH$, KOH

THE NUMBER OF STRONG BASES (BASES THAT ARE PRESENT IN SOLUTION LARGELY AS METAL IONS AND HYDROXIDE IONS RATHER THAN AS MOLECULES) IS NOT LARGE, AND THESE SHOULD BE LEARNED.
   $LiOH$ lithium hydroxide
   $NaOH$ sodium hydroxide
   KOH potassium hydroxide also $RbOH$ all IA
   $Ca(OH)_2$ calcium hydroxide $CsOH$
   $Sr(OH)_2$ strontium hydroxide
   $Ba(OH)_2$ barium hydroxide

3. METAL OXIDES - BINARY COMOUNDS OF A METAL AND OXYGEN
   CaO
   METAL OXIDES (BASIC ANHYDRIDES) REACT WITH WATER TO FORM METALLIC HYDROXIDE. IF THESE ARE SOLUBLE THEY THEN PROVIDE HYDROXIDE IONS AND ARE THUS BASES IN WATER SOLUTION.

4. NONMETAL OXIDES - BINARY COMPOUNDS OF A METAL AND OXYGEN
   SO_2
   NONMETAL OXIDES (ACID ANHYDRIDES) REACT WITH WATER TO FORM ACIDS.

5. SALTS - COMPOUNDS OF METALS THAT ARE NOT BASES OR METAL OXIDES
   $NaCl$, MgS, $ZnSO_4$
   THE SALTS THAT ARE SOLUBLE IN WATER INCLUDE ALL OF THE SALTS OF LITHIUM, SODIUM, POTASSIUM, AND AMMONIUM CATIONS AND OF NITRATE AND ACETATE ANIONS. ALL CHLORIDE ARE SOLUBLE EXCEPT THOSE OF SILVER, LEAD AND MERCURY(I) IONS. ALL SULFATES ARE SOLUBLE EXCEPT THOSE OF LEAD, CALCIUM, STRONTIUM AND BARIUM. ALL OTHER SALTS SHOULD BE CONSISERED ONLY SLIGHTLY SOLUBLE UNLESS AND UNTIL ONE LEARNS OTHERWISE.

6. OTHER COMPOUNDS (MOST COMPOUNDS BELONG HERE.)
   CH_4, NH_3

****
WHEN REPRESENTING A REACTION THAT OCCURS IN WATER SOLUTION, THE SUBSTANCES THAT SHOULD BE WRITTEN AS IONS ARE THE STRONG ACIDS, STRONG BASES, AND THE SOLUBLE SALTS.
****

IN ADDITION KEEP IN MIND

A. UNSTABLE MOLECULES
H_2CO_3-----> H_2O + CO_2
H_2SO_3 -----> H_2O + SO_2
NH_4OH ---> NH_3 + H_2O

B. ACID ANHYDRIDES - NONMETALLIC OXIDES
SO_3 , CO_2, SO_2, N_2O_5
BASIC ANHYDRIDES - METALLIC OXIDES
CaO, MgO, Na_2O

C. AMPHOTERIC HYDROXIDES AND OXIDES OF METALS - FOR THESE REACTIONS THERE IS USUALLY AN EXCESS OF OH^- IONS
Al^{3+}, Cr^{3+}, Zn^{2+}, Sn^{2+}

EXAMPLE $Al(OH)_3$ + $3H^+$ ---> Al^{3+} + 3HOH
$Al(OH)_3$ + OH^- ---> $Al(OH)_4^-$

CHEMICAL REACTIONS AND EQUATION

SOME COMMON TYPES OF REACTIONS

A. REACTIONS INVOLVING CHANGES IN OXIDATION STATES

1. COMBINATION REACTIONS (SYNTHESIS)

A + B ---> C

TWO REACTANTS COMBINE TO FORM A SINGLE PRODUCT. MANY ELEMENTS REACT WITH ONE ANOTHER IN THIS FASHION TO FORM BINARY COMPOUNDS. THE SYMBOL FOR THE MORE ELECTROPOSITIVE ELEMENT IS WRITTEN FIRST AND VALENCE RELATIONS ARE USED TO OBTAIN THE FORMULA.

$C_{(s)}$ + $O_{2(g)}$ ------> $CO_{2(g)}$

$N_{2(g)}$ + $3H_{2(g)}$ -----> $2NH_{3(g)}$

ALSO - AN OXIDIZER WILL REACT WITH A REDUCER OF THE SAME ELEMENT TO PRODUCE THE ELEMENT AT AN INTERMEDIATE OXIDATION STATE.
EXAMPLES:
SOLUTIONS OF POTASSIUM IODIDE, POTASSIUM IODATE, AND DILUTE SULFURIC ACID ARE MIXED
I^- + IO_3^- + H^+ ---> I_2 + H_2O

A PIECE OF IRON IS ADDED TO A SOLUTION OF IRON(III) SULFATE

$Fe + Fe^{3+} \text{ ----> } Fe^{2+}$

2. REACTIONS BETWEEN AN OXIDIZER AND A REDUCER
PRODUCTS FROM SUCH REACTIONS CAN USUALLY BE PREDICTED FROM KNOWLEDGE ABOUT A LIMITED NUMBER OF OXIDIZERS AND REDUCERS.

IMPORTANT OXIDIZERS	FORMED IN THE REACTION
MnO_4^- IN ACID SOL.	Mn^{2+}
MnO_2 IN ACID SOL.	Mn^{2+}
MnO_4^- IN NEUTRAL OR BASIC SOL.	MnO_2
$Cr_2O_7^{2-}$ IN ACID SOL	Cr^{3+}
HNO_3 CONCENTRATED	NO_2
HNO_3 DILUTE	NO
H_2SO_4 HOT CONCENTRATED	SO_2
METAL IC IONS	METAL OUS IONS
FREE HALOGENS	HALIDE IONS
Na_2O_2	NaOH
$HClO_4$	Cl^-

IMPORTANT REDUCERS	FORMED IN THE REACTION
HALIDE IONS	FREE HALOGEN
FREE METALS	METAL IONS
SULFITE IONS (OR SO_2)	SULFATE IONS
NITRITE IONS	NITRATE IONS
FREE HALOGENS, DIL BASIC SOLN	HYPOHALITE IONS
FREE HALOGENS, CONC. BASIC SOLN.	HALATE IONS
METAL OUS IONS	METAL IC IONS

TO PREDICT PRODUCTS OF A REACTION THAT FITS INTO THIS CATEGORY LOOK AT THE REAGENTS GIVEN IN THE QUESTION TO SEE IF THERE ARE

AVAILABLE BOTH AN OXIDIZER AND A REDUCER. THIS STEP MAY INVOLVE RECOGNIZING THE IONS THAT ARE PARTS OF THE COMPOUNDS LISTED AS THE REAGENTS. THEN ONE CAN WRITE THE APPROPRIATE PRODUCTS FROM THE OXIDER AND THE REDUCER PRESENT. KEEP IN MIND THE ACID OR THE BASE PRESENT IF AN ACID OR A BASE IS LISTED AS A REACTANT. IN ACIDIC SOLUTIONS, ANY METAL IONS FORMED CAN COMBINE WITH THE ANION OF THE ACID TO FORM SALTS. KEEP IN MIND THE SOLUBILITIES OF THE SALTS THEN PREDICT IF THE PRODUCTS INCLUDE A PRECIPITATED SALT OR WHETHER IONS ARE THE APPROPRIATE PRODUCTS.

REDOX REACTIONS ARE OFTEN RECOGNIZED BY:
.... familiarization with important reducers and oxidizers
..... the clue that there is "added acid" or the solution is "acidified"
..... the use of the supplied reduction potential reference

Examples

Manganese dioxide is added to concentrated hydrochloric acid and heated.

$MnO_2 + H^+ \text{ ---> } Mn^{2+} + Cl_2 + H_2O$

A solution of iron(II) nitrate is added to an acidified solution of potassium permanganate.

$Fe^{2+} + H^+ + MnO_4^- \text{ ----> } Fe^{3+} + Mn^{2+} + H_2O$

Manganesium metal is added to dilute nitric acid. One of the products contains nitrogen with an oxidation number of -3.

$Mg \quad H^+ + NO_3^- \text{ ---> } Mg^{2+} + NH_3 + H_2O$

(INFORMATION ABOUT BASIC SOLUTIONS WILL FOLLOW)

3. SOME DECOMPOSITON REACTIONS INVOLVE REDOX

$$C \text{ ----> } A + B$$

A SINGLE REACTANT BREAKS APART TO FORM TWO OR MORE SUBSTANCES. MANY COMPOUNDS BEHAVE IN THIS FASHION WHEN HEATED.

CHLORATES DECOMPOSE IN THE PRESENCE OF HEAT

$$2KClO_{3(s)} \text{ ----> } 2KCl_{(s)} + 3O_{2(g)}$$

A SOLUTION OF HYDROGEN PEROXIDE IS CATALYTICALLY DECOMPOSED

$$H_2O_2 \text{ ------> } H_2O + O_2$$

ELECTROLYSIS DECOMPOSES COMPOUNDS INTO THEIR ELEMENTS

$$H_2O \text{ ---> } H_2 + O_2$$

4. SINGLE DISPLACEMENT REACTIONS -ALL SINGLE REPLACEMENT REACTIONS ARE REDOX.

$$A+BX \text{ ----> } AX + B$$

ONE ELEMENT REPLACES ANOTHER IN A COMPOUND. (THE ELEMENTS ARE OFTEN HYDROGEN AND A METAL)
A MORE REACTIVE ELEMENT (OFTEN IN THE FREE STATE CAN DISPLACE A LESS REACTIVE ELEMENT WITH SIMILAR PROPERTIES FROM A COMPOUND.

A very active metal replaces hydrogen from water.

$$2Na_{(s)} + 2H_2O \text{ ----> } 2NaOH_{(aq)} + H_{2(g)}$$

A metal above hydrogen on the activity scale replaces hydrogen from and acid

$$Fe_{(s)} + 2HCl_{(aq)} \text{ ----> } FeCl_{2(aq)} + H_{2(g)}$$

A more active metal replaces a less active metal from a compound

$$Zn_{(s)} + CuSO_{4(aq)} \text{ -----> } ZnSO_{4(aq)} + Cu_{(s)}$$

A more active halogen replaces a less active halogen from a compound

$$Cl_2 + 2LiBr \text{ -----> } 2LiCl + Br_2$$

B. REACTIONS INVOLVING NO CHANGES IN OXIDATION STATES

1. DOUBLE DISPLACEMENT (METATHESIS) REACTIONS

$$AX + BY \text{ ----> } AY + BX$$

ATOMS OR IONS EXCHANGE PARTNERS.
THESE REACTION START WITH TWO REACTANTS AND PRODUCE TWO PRODUCTS. SUCH REACTIONS CAN BE EXPECTED WHEN THE TWO REACTANTS COME FROM THE TYPES OF COMPOUNDS : ACID, BASE, SALT AND WATER (FOR CONVENIENCE WRITTEN AS HOH) THE PRODUCTS CAN BE PREDICTED BY EXCHANGING THE POSITIVE PARTS OF THE TWO REACTANTS. THE PRODUCTS ARE FROM THE SAME TYPES OF COMPOUNDS.

$$HCl + NaOH \text{ ---> } NaCl + HOH$$

ONE THEN USES THE INFORMATION PREVIOUSLY PRESENTED TO DECIDE WHICH OF THE SUBSTANCES SHOULD BE WRITTEN AS IONS. HCl IS A STRONG ACID, NaOH IS A STRONG BASE. AND NaCl IS A SOLUBLE SALT, AND SO ALL THREE SHOULD BE WRITTEN AS IONS. SINCE SUBDSTANCES THAT DO NOT CHANGE ARE NOT APPROPRIATELY REPRESENTED IN A

CHEMICAL REACTION OR A CHEMICAL EQUATION THE REACTION ABOVE BECOMES

H^{+}. + OH^{-} --> HOH (NET IONIC EQUATION - SPECTATOR IONS REMOVED)

$BaBr_{2(aq)} + K_2SO_{4(aq)} \text{ ---> } BaSO_{4(s)} + 2KBr_{(aq)}$

$Ca(OH)_{2(aq)} + 2HCl_{(aq)} \text{ -----> } CaCl_{2(aq)} + 2H_2O_{(l)}$

2. SOME COMBINATION REACTIONS RELATED TO METATHETICAL REACTIONS. THESE REACTIONS PRODUCE A SINGLE PRODUCT PREDICTABLE FROM THE TYPES OF THE REACTANTS INDICATED WITH EACH OF THE EXAMPLES BELOW.

METAL OXIDE + WATER ----> A BASE, THE METAL IN THE SAME OXIDATION STATE AS IN THE OXIDE.

$CaO_{(s)} + HOH_{(l)} \text{ ------> } Ca(OH)_{2(aq)}$

THEN REVISED TO

$CaO_{(s)} + HOH \text{ ---> } Ca^{2+} + OH^{-}$

NONMETAL OXIDE + WATER ---> AN ACID, THE NONMETAL IN THE SAME OXIDATION STATE AS IN THE OXIDE

$SO_2 + HOH \text{ ----> } H_2SO_3$

(NO STRONG ACID OR STRONG BASE OR SOLUBLE SALT, SO NO IONS)

METAL OXIDE + NONMETAL OXIDE ----> SALT, WITH THE NONMETAL APPEARING IN A RADICAL (POLYATOMIC ION) WHERE IT HAS THE SAME OXIDATION STATE AS IN THE OXIDE

$CaO + SO_2 \text{ ----> } CaSO_3$

(_NO STRONG ACID OR BASE OR SOLUBLE SALT, SO NO IONS)

3. SOME DECOMPOSITION REACTIONS (THE REVERSE OF THE COMBINATION REACTIONS IN THE CATEGORY RELATED TO METATHETICAL REACTIONS THERE IS ONE REACTANT AND THERE ARE TWO PRODUCTS IN EACH OF THESE REACTIONS

BASE ---> METAL OXIDE + WATER

$Ca(OH)_{2\ (s)} \text{ ----> } CaO_{\ (s)} + HOH$

ACID CONTAINING OXYGEN ---> NONMETAL OXIDE AND WATER

$H_2CO_{3(aq)} \text{ ----> } H_2O(l) + CO_{2(g)}$

$H_2SO_{3(aq)} \text{ ----> } H_2O(l) + SO_{2(g)}$

$HNO_3(aq) \text{ ------> } H_2O(l) + NO_{2(g)}$

HEATED $H_2SO_{4(aq)}$ ----> $H_2O(l)$ + $SO_{3(g)}$

SALT CONTAINING OXYGEN OXYGEN ---> METAL OXIDE + NONMETAL OXIDE

$CaCO_{3(s)}$ ---> $CaO_{(s)}$ + $CO_{2(g)}$

4. HYDROLYSIS REACTIONS

THE REACTIONS OF SALTS WITH WATER CAN USUALLY BE HANDLED AS METHATHETICAL REACTIONS. IN ADDITION TO SALTS, SOME OF THE other COMPOUNDS, PARTICULARLY NONMETALLIC HALIDES, REACT WITH WATER. IF THE WATER IS WRITTEN AS HOH, COMBINING THE H FROM THE WATER WITH THE MORE (OR MOST) ELECTRONEGATIVE ELEMENT FROM THE OTHER COMPOUND USUALLY GIVES THE FORMULA FOR ONE OF THE PRODUCTS. THE OTHER PRODUCT CONTAINS THE REMAINING ELEMENTS. THE FORMULA FOR THIS SECOND COMPOUND USUALLY NEEDS TO BE REARRANGED IN ORDER TO MAKE CLEAR ITS ACIDIC PROPERTIES.

PCl_3 + HOH ---> HCl + $P(OH)_3$ REARRANGED TO H_3PO_3 OR MORE ACCURATELY, TO H_2PHO_3

5. REACTIONS OF COORDINATION COMPOUNDS AND IONS

FREQUENTLY EXCESS AMMONIA IS USED OR 15 M AMMONIUM HYDROXIDE THE LIGANDS MOST FREQUENTLY CONSIDERED, ATTACHED TO A CENTRAL ATOM THAT IS USUALLY A METAL ION, ARE THE AMMONIA MOLECULE AND THE HYDROXIDE ION.

KEEP IN MIND THAT THE NUMBER OF LIGANDS ATTACHED TO A CENTRAL METAL ION IS SOMETIMES TWICE THE OXIDATION NUMBER OF THE CENTRAL METAL: $Ag(NH_3)_2^+$, $Zn(OH)_4^{2+}$

THE BREAKUP OF THESE COORDINATION IONS IS FREQUENTLY ACHIEVED BY ADDING AN ACID. THE PRODUCTS ARE THE METAL ION AND THE SPECIES FORMED WHEN HYDROGEN IONS FROM THE ACID REACT WITH THE LIGAND (NH_4^+ FROM NH_3 AND HOH FROM OH^-)

$Al(OH)_4^-$ + H^+ --> Al^{3+} + HOH

6. REACTIONS BASED ON NONWATER DEFINITIONS OF ACIDS AND BASES

BOTH BRONSTED AND LEWIS DEFINITIONS OF ACIDS AND BASES CAN BE ILLUSTRATED BY THE WRITING OF EQUATIONS. RECOGNIZING THAT AN ACID AND A BASE ARE THE REACTANTS ACCORDING TO ONE OF THE DEFINITIONS AND KNOWING HOW THEY REACT IS THE BEST APPROACH. BRONSTED REACTIONS INVOLVE THE TRANSFER OF A PROTON. LEWIS REACTIONS INVOLVE THE FORMATION OF A COORDINATE COVALENT BOND.

KEEP IN MIND LEWIS ACIDS AND BASES (NH_3 + BF_3) AND ANHYDRIDES SUCH AS CaO + SO_3

C. ORGANIC REACTIONS - THE MOST COMMON TYPE OF REACTIONS ARE:

1. ADDITION REACTIONS - AKENE OR ALKYNE PLUS HALOGEN OR HALIDE - OBSERVES MARKOVNIKOFF'S RULE (WHEN A HYDROGEN HALIDE IS ADDED TO AN ALKENE, THE HYDROGEN ATOM NORMALLY ENDS UP ON THE CARBON ATOM THAT ALREADY HAS THE MOST HYDROGEN ATOMS.
2. FORMATION OF ALCOHOLS VIA ADDITION REACTION
3. ESTERIFICATION - ACID PLUS ALCOHOL GIVES AN ESTER PLUS WATER.

Redox: Combination reactions.

An oxidizer will react with a reducer of the same element to produce the element at an intermediate oxidation state.

Examples:

1. Solutions of potassium iodide, potassium iodate, and dilute sulfuric acid are mixed.

   $I^- + IO_3^- + H^+ \Rightarrow I_2 + H_2O$

2. A piece of iron is added to a solution of iron (III) sulfate.

   $Fe + Fe^{3+} \Rightarrow Fe^{2+}$

Redox: Replacement reactions.

A more reactive element (often in the free state) can displace a less reactive element with similar properties from a compound.

Examples:

1. Zinc metal reacts with tin (II) sulfate.

   $Zn + Sn^{2+} \Rightarrow Zn^{2+} + Sn$

2. Free chlorine reacts with sodium bromide.

   $Cl_2 + Br^- \Rightarrow Cl^- + Br_2$

3. Solid barium peroxide is added to cold sulfuric acid.

   $BaO_2 + H^+ + SO_4^{2-} \Rightarrow BaSO_4 + H_2O_2$

Redox: Decomposition reactions

Examples:

1. A solution of hydrogen peroxide is catalytically decomposed.

   $H_2O_2 \Rightarrow H_2O + O_2$

2. Chlorates decompose in the presence of heat.

   $KClO_3 \Rightarrow KCl + O_2$

3. Electrolysis decomposes compounds into their elements.

   $H_2O \Rightarrow H_2 + O_2$

Name________________________________

Problem

A salt contains only barium and one of the halide ions. A 0.158 g sample of the salt was dissolved in water, and an excess of sulfuric acid was added to form barium sulfate ($BaSO_4$), which was filtered, dried, and weighed. Its mass was found to be 0.124 g. What is the formula of the barium halide?

LIMITING REACTANT AND THEORETICAL YIELD

✓

- THE **REACTANT IN EXCESS** IS THE SUBSTANCE WHICH WILL HAVE SOME *LEFT OVERS.*
- THE **LIMITING REACTANT** IS THE SUBSTANCE WHICH WILL BE ENTIRELY CONSUMED IN THE REACTION.
- *THE* ***THEORETICAL YIELD*** *IS THE AMOUNT OF PRODUCT THAT WOULD BE FORMED IF ALL OF THE LIMITING REACTANT WERE CONSUMED.*

Often, you will be told the amounts of two different reactants and asked to determine which is the limiting reactant and calculate the theoretical yield of product. To do this, it helps to follow a systematic procedure.

1. *Calculate the amount of product that would be formed if the first reactant were completely consumed.*
2. *Repeat this calculation for the second reactant; that is calculate how much product would be formed if all of that reactant were consumed.*
3. *Choose the smaller of the two amounts calculated in 1 and 2. This is the theoretical yield of product; the reactant that produces the smaller amount is the limiting reactant. The other reactant is in excess; only part of it is consumed.*

Example:

Consider the reaction

$2\ Sb + 3\ I_2 \text{ ---> } 2\ SbI_3$

Determine the limiting reactant and the theoretical yield of product if we start with
a. 1.20 mol Sb and 2.40 mol I_2

b. 1.20 g Sb and 2.40 g I_2

REMEMBER IN DECIDING UPON THE THEORETICAL YIELD OF PRODUCT YOU CHOOSE THE SMALLER OF THE TWO CALCULATED AMOUNTS.

THE ACTUAL YIELD IS WHAT YOU GET. THE THEORETICAL YIELD IS WHAT YOU WOULD GET IF EVERYTHING IN THE EXPERIMENT WENT PERFECTLY.

LIMITING REACTANTS CONTINUED

ANOTHER METHOD TO FIND LIMITING REACTANTS

1. FIND THE MOLAR MASS OF ALL SUBSTANCES IN THE PROBLEM.
2. FIND THE NUMBER OF MOLES OF EACH OF THE REACTANTS.
3. DIVIDE THE REACTANTS MOLES BY THEIR RESPECTIVE COEFFICIENTS – THIS TELLS THE NUMBER OF TIMES THE REACTION CAN RUN.
4. THE REACTANT WITH THE FEWEST NUMBER OF TIMES IS THE LIMITING REACTANT

AP 1991 B

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The molecular formula of a hydrocarbon is to be determined by analyzing its combustion products and investigating its colligative properties.

a. the hydrocarbon burns completely, producing 7.2 g of water and 7.2 liters of CO_2 at standard conditions. what is the empirical formula of the hydrocarbon?

std. conditions (0°C & 1atm)
means 1 mole of any
gas will occupy 22.4L

b. calculate the mass in grams of O_2 required for the complete combustion of the sample of the hydrocarbon described in a.

c. the hydrocarbon dissolves readily in $CHCl_3$ .The freezing point of a solution prepared by mixing 100 g of $CHCl_3$ —chloroform and 0.600 g of the hydrocarbon is -64.0 ° C. Calculate the molecular weight of the hydrocarbon.

ch.13

d. What is the molecular formula of the hydrocarbon?

✓

CHEMISTRY 2 AP

NAME____________________________

EQUATIONS OF THE WEEK #1

WRITE BALANCED NET EQUATIONS FOR THESE REACTIONS

A. COMPOSITION REACTIONS

1. MAGNESIUM METAL IS BURNED IN NITROGEN GAS

2. SULFUR DIOXIDE GAS IS PASSED OVER SOLID CALCIUM OXIDE

B. DECOMPOSITION REACTIONS

3. SOLID AMMONIUM CARBONATE IS HEATED

4. A SOLUTION OF HYDROGEN PEROXIDE IS CATALYTICALLY DECOMPOSED

REPLACEMENT REACTIONS

5. LEAD FOIL IS IMMERSED IN SILVER NITRATE SOLUTION

6. CHLORINE GAS IS BUBBLED INTO A SOLUTION OF SODIUM BROMIDE

PERIODIC TABLE OF THE ELEMENTS

Table of Selected Radioactive Isotopes

$_{0}$n	1	(15.3 min) β^-
$_{1}$H	3	(12.26 y) β^-
$_{4}$Be	7	(53.3 d) EC
	10	(1.6 × 10^6 y) β^-
$_{6}$C	11	(20.40 min) β^+
	14	(5730 y) β^-
$_{9}$F	18	(109.8 min) β^+
$_{11}$Na	22	(2.602 y) β^+, EC
	24	(15.02 h) β^-
$_{12}$Mg	28	(20.9 h) β^-
$_{13}$Al	26	(7.2 × 10^5 y) β^+, EC
$_{15}$P	32	(14.26 d) β^-
$_{16}$S	35	(87.2 d) β^-
$_{17}$Cl	36	(3.01 × 10^5 y) β^-
	38	(37.2 min) β^-
$_{18}$Ar	37	(35.02 d) EC
	39	(265 y) β^-
$_{19}$K	40	(1.28 × 10^9 y) β^-, EC
	42	(12.36 h) β^-
$_{20}$Ca	45	(165 d) β^-
$_{21}$Sc	46	(83.80 d) β^-
$_{24}$Cr	51	(27.70 d) EC
$_{25}$Mn	53	(2 × 10^6 y) EC
	54	(312.0 d) EC
	56	(2.578 h) β^-
$_{26}$Fe	59	(44.6 d) β^-
$_{27}$Co	56	(78.8 d) β^+, EC
	57	(270 d) EC
	58	(71.3 d) β^+, EC
	60	(5.272 y) β^-
$_{28}$Ni	57	(36.0 h) β^+, EC
	59	(8 × 10^4 y) EC
	63	(92 y) β^-
$_{29}$Cu	64	(12.70 h) β^-, β^+, EC
	67	(61.88 h) β^-
$_{30}$Zn	65	(244.1 d) β^+, EC
$_{31}$Ga	67	(78.2 h) EC
	72	(14.10 h) β^-
$_{32}$Ge	68	(275 d) EC
$_{33}$As	73	(80.3 d) EC
	74	(17.9 d) β^-, β^+, EC
$_{34}$Se	75	(118.5 d) β
	79	(6.5 × 10^4 y) β^-
$_{35}$Br	82	(35.34 h) β^-
$_{36}$Kr	81	(2.1 × 10^5 y) EC
	85	(10.72 y) β^-
$_{37}$Rb	86	(18.7 d) β^-
	87	(4.8 × 10^{10} y) β^-
$_{38}$Sr	90	(28.8 y) β^-
$_{39}$Y	88	(106.6 d) β^+, EC
$_{40}$Zr	93	(1.5 × 10^6 y) β^-
	95	(64.0 d) β^-
$_{41}$Nb	94	(2.0 × 10^4 y) β^-
	95	(35.15 d) β^-
$_{42}$Mo	99	(66.02 h) β^-
$_{43}$Tc	97	(2.6 × 10^6 y) EC
	98	(4.2 × 10^6 y) β^-
	99	(2.13 × 10^5 y) β^-
$_{44}$Ru	106	(367 d) β^-
$_{45}$Rh	101	(3.3 y) EC
$_{46}$Pd	103	(17.0 d) EC
	107	(7 × 10^6 y) β^-
$_{47}$Ag	108	(127 y) EC
	110	(252 d) β^-
	111	(7.45 d) β^-
$_{48}$Cd	109	(453 d) EC
$_{49}$In	114	(49.51 d) IT
$_{50}$Sn	121	(76 y) β^-
$_{51}$Sb	124	(60.20 d) β^-
	125	(2.7 y) β^-
$_{52}$Te	121 m	(154 d) IT
	123 m	(119.7 d) IT
	127 m	(109 d) IT
$_{53}$I	129	(1.6 × 10^7 y) β^-
	131	(8.040 d) β^-
$_{54}$Xe	133	(5.25 d) β^-
	135	(9.10 h) β^-
$_{55}$Cs	134	(2.06 y) β^-
	135	(2.9 × 10^6 y) β^-
	137	(30.17 y) β^-
$_{56}$Ba	140	(12.8 d) β^-
$_{57}$La	137	(6 × 10^4 y) EC
	140	(40.3 h) β^-
$_{58}$Ce	144	(284 d) β^-
$_{59}$Pr	142	(19.1 h) β^-
$_{60}$Nd	147	(11.1 d) β^-
$_{61}$Pm	145	(18 y) EC
	147	(2.62 y) β^-
$_{62}$Sm	146	(7 × 10^7 y) α
	151	(93 y) β^-
$_{63}$Eu	152	(13 y) β^-, EC, β^+
	154	(8.5 y) β^-
$_{64}$Gd	150	(2.1 × 10^6 y) α
$_{65}$Tb	158	(1.2 × 10^3 y) EC, β^-
	160	(72.3 d) β^-
$_{67}$Ho	166 m	(1.2 × 10^3 y) β^-
$_{69}$Tm	170	(128.6 d) β^-
	171	(1.92 y) β^-
$_{70}$Yb	169	(32.0 d) EC
	175	(4.19 d) β^-
$_{71}$Lu	176	(3.7 × 10^{10} y) β^-
$_{73}$Ta	182	(115.0 d) β^-
$_{74}$W	181	(140 d) EC
	185	(75.1 d) β^-
	188	(69 d) β^-
$_{75}$Re	187	(5 × 10^{10} y) β^-
$_{76}$Os	194	(6.0 y) β^-
$_{77}$Ir	192	(74.2 d) β^-, β^+, EC
$_{79}$Au	195	(183 d) EC
	196	(6.18 d) β^+, EC, β^-
	198	(2.696 d) β^-
	199	(3.15 d) β^-
$_{80}$Hg	203	(46.8 d) β^-
$_{81}$Tl	204	(3.77 y) β^-
$_{82}$Pb	202	(3 × 10^5 y) EC
	205	(3 × 10^7 y) EC
	210	(22.3 y) β^-, α
$_{83}$Bi	207	(38 y) EC
	208	(3.7 × 10^5 y) EC
	210	(5.01 d) β^-, α
	210 m	(3 × 10^6 y) α
$_{84}$Po	208	(2.90 y) α
	209	(102 y) α
	210	(138.38 d) α
$_{85}$At	209	(5.4 h) EC, α
	210	(8.1 h) EC
	211	(7.21 h) EC, α
$_{86}$Rn	222	(3.824 d) α
$_{87}$Fr	212	(19.3 min) EC, α
	222	(15 min) β^-
	223	(21.8 min) β^-
$_{88}$Ra	226	(1.60 × 10^3 y) α
$_{89}$Ac	227	(21.77 y) β^-
$_{90}$Th	228	(1.913 y) α
	230	(7.7 × 10^4 y) α
	232	(1.40 × 10^{10} y) α
$_{91}$Pa	231	(3.28 × 10^4 y) α
$_{92}$U	233	(1.59 × 10^5 y) α
	234	(2.44 × 10^5 y) α
	235	(7.04 × 10^8 y) α
	236	(2.34 × 10^7 y) α
	238	(4.47 × 10^9 y) α
$_{93}$Np	236	(1.1 × 10^5 y) EC, β^-
	237	(2.14 × 10^6 y) α
	239	(2.346 d) β^-
$_{94}$Pu	238	(87.75 y) α
	239	(2.41 × 10^4 y) α
	240	(6.54 × 10^3 y) α
	242	(3.8 × 10^5 y) α
	244	(8.3 × 10^7 y) α
$_{95}$Am	241	(432 y) α
	243	(7.37 × 10^3 y) α
$_{96}$Cm	242	(163.2 d) α
	244	(18.12 y) α
	247	(1.55 × 10^7 y) α
	248	(3.5 × 10^5 y) α, SF
$_{97}$Bk	247	(1.4 × 10^3 y) α
$_{98}$Cf	249	(351 y) α
	251	(900 y) α
$_{99}$Es	252	(472 d) α
	253	(20.47 d) α
	254	(276 d) α
$_{100}$Fm	255	(20.1 h) α
	257	(100.5 d) α
$_{101}$Md	258	(55 d) α
$_{102}$No	259	(58 min) α
$_{103}$Lr	260	(3.0 min) α
$_{104}$Rf	261	(65 s) α
$_{105}$Db	262	(40 s) α
$_{106}$Sg	263	(0.9 s) α

Selected Radioactive Isotopes

Naturally occurring radioactive isotopes are designated by a mass number in blue (although some are also manufactured). Letter m indicates an isomer of another isotope of the same mass number. Half-lives follow in parentheses, where s, min, h, d, and y stand respectively for seconds, minutes, hours, days, and years. The table includes mainly the longer-lived radioactive isotopes; many others have been prepared. Isotopes known to be radioactive but with half-lives exceeding 10^{17} y have not been included. Symbols describing the principal mode (or modes) of decay are as follows (these processes are generally accompanied by gamma radiation)

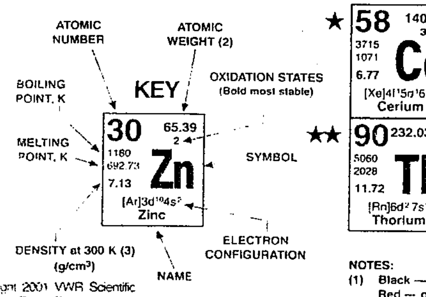
α	alpha particle emission
β^-	beta particle (electron) emission
β^+	positron emission
EC	orbital electron capture
IT	isomeric transition from upper to lower isomeric state
SF	spontaneous fission

GROUP

1/IA	2/IIA	3/IIIA	4/IVA	5/VA	6/VIA	7/VIIA	8	9 VIIIA	10	11/IB	12/IIB	13/IIIB	14/IVB	15/VB	16/VIB	17/VIIB	18/VIII
1 1.00794 1 20.28 13.81 0.0899 † H $1s^1$ Hydrogen																	2 4.00260 4.216 0.95 at 26 atm 0.1785† He $1s^2$ Helium
3 6.941 1 1615 453.7 0.53 Li $1s^22s^1$ Lithium	4 9.01218 2 3243 1560 1.85 Be $1s^22s^2$ Beryllium											5 10.811 3 4275 2365 2.34 B $1s^22s^2p^1$ Boron	6 12.011 ±4,2 5100* 3825* 2.26 C $1s^22s^2p^2$ Carbon	7 14.0067 ±3,5,4,2 77.344 63.15 1.251† N $1s^22s^2p^3$ Nitrogen	8 15.9994 -2 90.188 54.8 1.429† O $1s^22s^2p^4$ Oxygen	9 18.99840 -1 85.0 53.55 1.696† F $1s^22s^2p^5$ Fluorine	10 20.1797 27.10 24.55 0.900† Ne $1s^22s^2p^6$ Neon
11 22.98977 1 1156 371.0 0.97 Na $[Ne]3s^1$ Sodium	12 24.305 2 1380 922 1.74 Mg $[Ne]3s^2$ Magnesium											13 26.98154 3 2740 933.5 2.70 Al $[Ne]3s^2p^1$ Aluminum	14 28.0855 4,2 2630 1683 2.33 Si $[Ne]3s^2p^2$ Silicon	15 30.97376 ±3,5,4 553 317.3 1.82 P $[Ne]3s^2p^3$ Phosphorus	16 32.066 ±2,4,6 717.82 392.2 2.07 S $[Ne]3s^2p^4$ Sulfur	17 35.4527 ±1,3,5,7 239.18 172.17 3.214† Cl $[Ne]3s^2p^5$ Chlorine	18 39.948 87.45 83.95 1.784† Ar $[Ne]3s^2p^6$ Argon
19 39.0983 1 1033 336.8 0.86 K $[Ar]4s^1$ Potassium	20 40.078 2 1757 1112 1.55 Ca $[Ar]4s^2$ Calcium	21 44.9559 3 3109 1814 2.99 Sc $[Ar]3d^14s^2$ Scandium	22 47.87 4,3 3560 1935 4.54 Ti $[Ar]3d^24s^2$ Titanium	23 50.9415 5,4,3,2 3650 2163 6.11 V $[Ar]3d^34s^2$ Vanadium	24 51.996 6,3,2 2945 2130 7.19 Cr $[Ar]3d^54s^1$ Chromium	25 54.9380 7,6,4,2,3 2235 1518 7.44 Mn $[Ar]3d^54s^2$ Manganese	26 55.845 2,3,6 3023 1808 7.874 Fe $[Ar]3d^64s^2$ Iron	27 58.9332 2,3 3143 1768 8.90 Co $[Ar]3d^74s^2$ Cobalt	28 58.6934 2,3 3005 1726 8.90 Ni $[Ar]3d^84s^2$ Nickel	29 63.546 2,1 2840 1356.6 8.96 Cu $[Ar]3d^{10}4s^1$ Copper	30 65.39 2 1180 692.73 7.13 Zn $[Ar]3d^{10}4s^2$ Zinc	31 69.723 3 2478 302.92 5.91 Ga $[Ar]3d^{10}4s^2p^1$ Gallium	32 72.61 4 3107 1211.5 5.32 Ge $[Ar]3d^{10}4s^2p^2$ Germanium	33 74.9216 ±3,5 876 1090 5.78 As $[Ar]3d^{10}4s^2p^3$ Arsenic	34 78.96 -2,4,6 958 494 4.79 Se $[Ar]3d^{10}4s^2p^4$ Selenium	35 79.904 ±1,5,7 331.85 265.95 3.12 Br $[Ar]3d^{10}4s^2p^5$ Bromine	36 83.80 0,2 120.85 116 3.75† Kr $[Ar]3d^{10}4s^2p^6$ Krypton
37 85.4678 1 961 312.63 1.532 Rb $[Kr]5s^1$ Rubidium	38 87.62 2 1655 1042 2.54 Sr $[Kr]5s^2$ Strontium	39 88.9059 3 3611 1795 4.47 Y $[Kr]4d^15s^2$ Yttrium	40 91.224 4 4682 2128 6.51 Zr $[Kr]4d^25s^2$ Zirconium	41 92.9064 5,3 5015 2742 8.57 Nb $[Kr]4d^45s^1$ Niobium	42 95.94 6,5,4,3,2 4912 2896 10.22 Mo $[Kr]4d^55s^1$ Molybdenum	43 (98) 7 4538 2477 11.5 Tc $[Kr]4d^55s^2$ Technetium	44 101.07 2,3,4,6,8 4425 2610 12.37 Ru $[Kr]4d^75s^1$ Ruthenium	45 102.9055 2,3,4 3970 2236 12.41 Rh $[Kr]4d^85s^1$ Rhodium	46 106.42 2,4 3240 1825 12.0 Pd $[Kr]4d^{10}$ Palladium	47 107.868 1 2436 1235.08 10.50 Ag $[Kr]4d^{10}5s^1$ Silver	48 112.41 2 1040 594.26 8.65 Cd $[Kr]4d^{10}5s^2$ Cadmium	49 114.82 3 2350 429.78 7.31 In $[Kr]4d^{10}5s^2p^1$ Indium	50 118.710 4,2 2876 505.12 7.31 Sn $[Kr]4d^{10}5s^2p^2$ Tin	51 121.760 ±3,5 1860 903.91 6.69 Sb $[Kr]4d^{10}5s^2p^3$ Antimony	52 127.60 -2,4,6 1261 722.72 6.24 Te $[Kr]4d^{10}5s^2p^4$ Tellurium	53 126.9045 ±1,5,7 457.5 386.7 4.93 I $[Kr]4d^{10}5s^2p^5$ Iodine	54 131.29 0,2,4,6 165.1 161.39 5.90† Xe $[Kr]4d^{10}5s^2p^6$ Xenon
55 132.9054 1 944 301.54 1.87 Cs $[Xe]6s^1$ Cesium	56 137.33 2 2078 1002 3.59 Ba $[Xe]6s^2$ Barium	57 138.9055 3 ★ 3737 1191 6.15 La $[Xe]5d^16s^2$ Lanthanum	72 178.49 4 4875 2504 13.31 Hf $[Xe]4f^{14}5d^26s^2$ Hafnium	73 180.9479 5 5730 3293 16.65 Ta $[Xe]4f^{14}5d^36s^2$ Tantalum	74 183.84 6,5,4,3,2 5825 3695 19.3 W $[Xe]4f^{14}5d^46s^2$ Tungsten	75 186.207 7,6,4,2 5870 3455 21.0 Re $[Xe]4f^{14}5d^56s^2$ Rhenium	76 190.23 2,3,4,6,8 5300 3300 22.6 Os $[Xe]4f^{14}5d^66s^2$ Osmium	77 192.22 2,3,4,6 4700 2720 22.6 Ir $[Xe]4f^{14}5d^76s^2$ Iridium	78 195.08 2,4 4100 2042.1 21.45 Pt $[Xe]4f^{14}5d^96s^1$ Platinum	79 196.9665 3,1 3130 1337.58 19.3 Au $[Xe]4f^{14}5d^{10}6s^1$ Gold	80 200.59 2,1 629.88 234.31 13.55 Hg $[Xe]4f^{14}5d^{10}6s^2$ Mercury	81 204.383 3,1 1746 577 11.85 Tl $[Xe]4f^{14}5d^{10}6s^2p^1$ Thallium	82 207.2 4,2 2023 600.65 11.35 Pb $[Xe]4f^{14}5d^{10}6s^2p^2$ Lead	83 208.9804 3,5 1837 544.59 9.75 Bi $[Xe]4f^{14}5d^{10}6s^2p^3$ Bismuth	84 (209) 4,2,6 — 527 9.3 Po $[Xe]4f^{14}5d^{10}6s^2p^4$ Polonium	85 (210) ±1,3,5,7 610* 575 — At $[Xe]4f^{14}5d^{10}6s^2p^5$ Astatine	86 (222) 0,2 211.4 202 9.73 Rn $[Xe]4f^{14}5d^{10}6s^2p^6$ Radon
87 (223) 1 950 300 — Fr $[Rn]7s^1$ Francium	88 (226) 2 1413 973 5.0 Ra $[Rn]7s^2$ Radium	89 (227) 3 ★★ 3470* 1324 10.07 Ac $[Rn]6d^17s^2$ Actinium	104 (261) — — — Rf $[Rn]5f^{14}6d^27s^2$ Rutherfordium	105 (262) — — — Db $[Rn]5f^{14}6d^37s^2$ Dubnium	106 (263) — — — Sg $[Rn]5f^{14}6d^47s^2$ Seaborgium	107 (264) — — — Bh $[Rn]5f^{14}6d^57s^2$ Bohrium	108 (265) — — — Hs $[Rn]5f^{14}6d^67s^2$ Hassium	109 (268) — — — Mt $[Rn]5f^{14}6d^77s^2$ Meitnerium	110 (269) — — — Uun $[Rn]5f^{14}6d^87s^2$ (Ununnilium)	111 (272) — — — Uuu $[Rn]5f^{14}6d^97s^2$ (Unununium)	112 (277) — — — Uub $[Rn]5f^{14}6d^{10}7s^2$ (Ununbium)	113 (Ununtrium)	114 (285) — — — Uuq $[Rn]5f^{14}6d^{10}7s^27p^2$ (Ununquadium)	115 (Ununpentium)	116 (289) — — — Uuh $[Rn]5f^{14}6d^{10}7s^27p^4$ (Ununhexium)	117 (Unseptium)	118 (293) — — — Uuo $[Rn]5f^{14}6d^{10}7s^27p^6$ (Ununoctium)

* Estimated Values

★	58 140.12 3,4 3715 1071 6.77 Ce $[Xe]4f^15d^16s^2$ Cerium	59 140.9077 3,4 3785 1204 6.77 Pr $[Xe]4f^36s^2$ Praseodymium	60 144.24 3 3347 1294 7.01 Nd $[Xe]4f^46s^2$ Neodymium	61 (145) 3 3273 1315 7.22 Pm $[Xe]4f^56s^2$ Promethium	62 150.36 3,2 2067 1347 7.52 Sm $[Xe]4f^66s^2$ Samarium	63 151.964 3,2 1800 1095 5.24 Eu $[Xe]4f^76s^2$ Europium	64 157.25 3 3545 1585 7.90 Gd $[Xe]4f^75d^16s^2$ Gadolinium	65 158.9253 3,4 3500 1629 8.23 Tb $[Xe]4f^96s^2$ Terbium	66 162.50 3 2840 1685 8.55 Dy $[Xe]4f^{10}6s^2$ Dysprosium	67 164.9303 3 2968 1747 8.80 Ho $[Xe]4f^{11}6s^2$ Holmium	68 167.26 3 3140 1802 9.07 Er $[Xe]4f^{12}6s^2$ Erbium	69 168.9342 3,2 2223 1818 9.32 Tm $[Xe]4f^{13}6s^2$ Thulium	70 173.04 3,2 1469 1092 6.97 Yb $[Xe]4f^{14}6s^2$ Ytterbium	71 174.967 3 3668 1936 9.84 Lu $[Xe]4f^{14}5d^16s^2$ Lutetium
★★	90 232.0381 4 5060 2028 11.72 Th $[Rn]6d^27s^2$ Thorium	91 231.0359 5,4 4300* 1845 15.4 Pa $[Rn]5f^26d^17s^2$ Protactinium	92 238.029 6,5,4,3 4407 1408 18.95 U $[Rn]5f^36d^17s^2$ Uranium	93 (237) 6,5,4,3 4175* 912 20.2 Np $[Rn]5f^46d^17s^2$ Neptunium	94 (244) 6,5,4,3 3505 913 19.84 Pu $[Rn]5f^67s^2$ Plutonium	95 (243) 6,5,4,3 2880 1449 13.7 Am $[Rn]5f^77s^2$ Americium	96 (247) 3 — 1620 13.5 Cm $[Rn]5f^76d^17s^2$ Curium	97 (247) 4,3 — — 14* Bk $[Rn]5f^97s^2$ Berkelium	98 (251) 3 — 1170* — Cf $[Rn]5f^{10}7s^2$ Californium	99 (252) 3 — 1130* — Es $[Rn]5f^{11}7s^2$ Einsteinium	100 (257) 3 — 1800* — Fm $[Rn]5f^{12}7s^2$ Fermium	101 (258) 3 — 1100* — Md $[Rn]5f^{13}7s^2$ Mendelevium	102 (259) 2,3 — 1100* — No $[Rn]5f^{14}7s^2$ Nobelium	103 (262) 3 — 1900* — Lr $[Rn]5f^{14}6d^17s^2$ Lawrencium



NOTES:
(1) Black — solid.
Red — gas.
Blue — liquid.
Outline — synthetically prepared.
(2) Based upon carbon-12. ( ) indicates most stable or best known isotope.
(3) Entries marked with daggers refer to the gaseous state at 273 K and 1 atm and are given in units of g/l

The A & B subgroup designations, are those recommended by the International Union of Pure and Applied Chemistry.

VWR Scientific Products
Sargent-Welch